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Modelling Short Duration Shock Wave Attentuation in Explosives

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MRL Technical Note
MRL-TN-597

Abstract

The HULL hydrocode is used to predict the shock attentuation within a non-initiating explosive target following thin flyer plate impact. The attentuation relationship between the flyer plate thickness and the initial velocity is investigated. Agreement between HULL predictions and a simple theoretical model is provided. The HULL results may be employed to predict the maximum depth within which initiation may occur.

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Published by

Materials Research Laboratory
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AR No. 006-840

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1. Introduction

It is known that a shock wave attenuates as it travels through an inert medium [1,2]. The causes of this attenuation can be divided into two major groups. These are: (a) transfer of energy from the shock wave to the medium and (b) the degradation of the shock wave by the encroaching rarefaction waves. It is expected that similar attenuation mechanisms will occur within an explosive medium until the input stimulus initiates a reaction that may lead to a detonation.

It can be difficult to experimentally determine the extent of the attenuation within an explosive medium because that medium can respond to impact stimuli by quickly growing to detonation. If the impact duration is short the measurement becomes more difficult because the attenuation occurs over a short distance. An example of a short duration shock pulse that may lead to detonation is provided by the slapper detonator.

The slapper detonator [3] employs a thin flyer plate that impacts the surface of an explosive. At impact the shock intensity is measured in gigapascals and the shock duration in nanoseconds. This short duration high pressure shock pulse may cause initiation of the explosive.

Walker and Wasley [4] have proposed an initiation criterion of the form $P^n t$ = constant to quantify the effect of these parameters. In the equation, P is the shock pressure, t is the shock duration and n[1] is an experimentally determined constant for a specific material. Whatever the exact criterion may be, if initiation occurs, growth to detonation may ensue over a finite distance. Attenuation of the initiating shock wave, however, is still expected to occur prior to the onset of a reaction. In the cases where initiation does not occur, the transmitted shock wave undergoes further attenuation.

1 Schwarz [3] suggests that n = 2.4 for hexanitrostilbene (HNS).

By investigating the extent of the attenuation within the target and by employing an initiation criterion, it may be possible to predict whether a prompt or a delayed initiation will result or whether no initiation at all is possible. Such information could be employed to improve the understanding of short duration shock initiation.

In an attempt to quantify the attenuation, shock transmission through an explosive medium has been modelled. This was achieved by employing the hydrocode HULL [5].

2. *Numerical Model*

To simplify the calculation several assumptions were made. The explosive target was treated as an inert material as HULL is a non-reactive code. This is a reasonable assumption as the simulation was only concerned with the unreactive passage of the shock wave through the explosive. Shock initiation of the explosive was not of interest to this study.

The HULL code models attenuation of shock waves by changing the internal energy of the medium depending on the amount of work performed on that medium. The pressure, the deviatoric stresses and artificial viscosity terms are all employed to determine the amount of work performed. Conservation of total energy at the shock front is employed to determine the reduction in the shock wave velocity as the calculated internal energy of the shocked medium is increased. Further attenuation is achieved as the rarefaction wave encroaches upon the original shock wave and the particle velocity is returned to zero.

The problem to be modelled consisted of a thin, high velocity disc impacting a much longer stationary, cylindrical target (Fig. 1). The collision was modelled by HULL in Lagrangian mode. One dimensional geometry was employed as the width of the disc was large compared to the depth of penetration into the explosive that was expected and therefore the assumption of uniaxial strain close to the impact surface was valid. One dimensional geometry reduced the calculational time.

The same grid spacing was used for both the flyer plate and the target. The initial grid spacing was 0.5 μm for the x-axis and 1 μm for the y-axis. The 25 μm thick disc consisted of 286 nodes and the 375 μm long target of 4136 nodes. Later numerical experiments employed a thicker flyer plate (75 μm, 1111 nodes) against the same target.

Pressure-time history was determined at pre-selected points along the central axis of the disc and target. The data was analysed to determine the degree of attentuation of the pressure pulses.

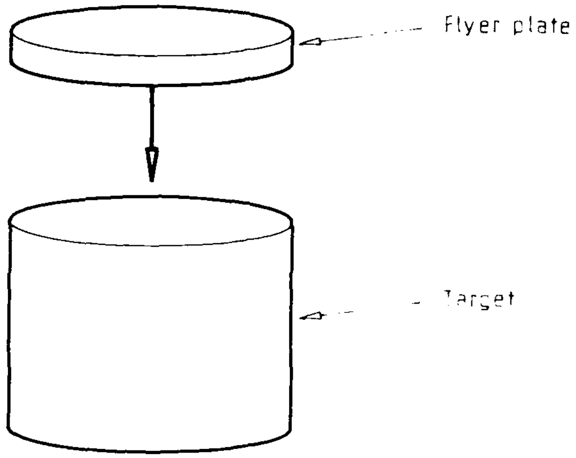

Figure 1: *Schematic showing the impact to be modelled. The shock wave is followed through the target.*

Code calculations were conducted for several different materials. These numerical experiments were employed to determine the credibility of the HULL output. Hugoniot data for the various materials used were inserted into the HULL material library. The Hugoniots for copper [5], hexanitrostilbene (HNS) [6] and Kapton (polyimide) [7] were:

$$\text{Copper:} \quad U_s = 3.958 + 1.497\, u_p \tag{1}$$

$$\text{HNS:} \quad U_s = 1.98 + 1.93\, u_p \tag{2}$$

$$\text{Kapton:} \quad U_s = 0.93 + 1.64\, u_p \tag{3}$$

where U_s is the shock velocity and u_p is the particle velocity, all in mm/μs. The densities of these materials were: 8900, 1570 and 1410 kg/m^3 respectively.

3. Results

The peak pressure, particle velocity and shock duration at the collision interface can be calculated from the known Hugoniots [1]. The code calculations can therefore be checked against the expected values at the interface. Such a

comparison should provide a clear indication of the validity of the code calculations at the shock interface. The results are shown in Table 1 for three separate cases with an impact velocity of 2.5 mm/µs: a copper disc impacting a copper target; a Kapton disc impacting a Kapton target and a Kapton disc impacting an HNS target. The flyer plate thickness was 25 µm. The simulations were successfully completed except for the Kapton colliding with Kapton where calculational instabilities were experienced in the HULL simulation.

Table 1: *Summary of HULL calculations and expected results [1] for various impact scenarios for a flyer plate 25 µm thick travelling at a velocity of 2.5 mm/µs.*

Impact Conditions		Hull			Impedance Matching		
Flyer	Target	P (GPa)	u_p (mm/µs)	t (ns)	P (GPa)	u_p (mm/µs)	t (ns)
copper	copper	62	1.27	8	65	1.25	9
Kapton	Kapton	-	-	-	7.8	1.25	11
Kapton	HNS	6.3	1.03	16	6.7	1.06	15

The pressure profiles predicted by HULL at the interface and within the HNS target can be seen in Figure 2. Successive profiles represent the pressure calculated at increasing depths of 25 µm up to a depth of 100 µm. The profiles are then shown at intervals of 50 µm.

In the ideal case, a square pulse is expected at the interface. The HULL calculation cannot provide a square pulse at the interface. This is partly due to the finite dimension of the cell sizes employed. Consequently the first calculated profile in the series shown in Figure 2, corresponds to a location beneath the surface of the target rather than at the interface. Attenuation would therefore have already begun and the HULL predictions for the shock pressure at the interface would be underestimated. In addition, the numerical techniques employed by HULL to solve the problem may also affect the accuracy of the predictions.

For the purposes of the comparison shown in Table 1, the initial shock duration for the Kapton/HNS impact was measured as follows. A horizontal line was drawn at the peak pressure of the first profile. The shock duration was estimated to correspond to the time that the pressure at the peak remained constant. At later times, the shock duration is quoted as the full width at half height (FWHH).

At the interface, good agreement was found between the impedance matching technique [1] and the HULL model as shown in Table 1. It was therefore decided to investigate the attenuation of the shock wave inside the target. This was done as a function of impact velocity and plate thickness for a Kapton flyer and an HNS target. A range of impact velocities that encompassed the experimentally derived threshold velocity of approximately 2.7 mm/µs [8] for 380 µm wide flyer plates and explosive HNS with a specific surface area (SSA) of approximately 8 m^2/g were chosen.

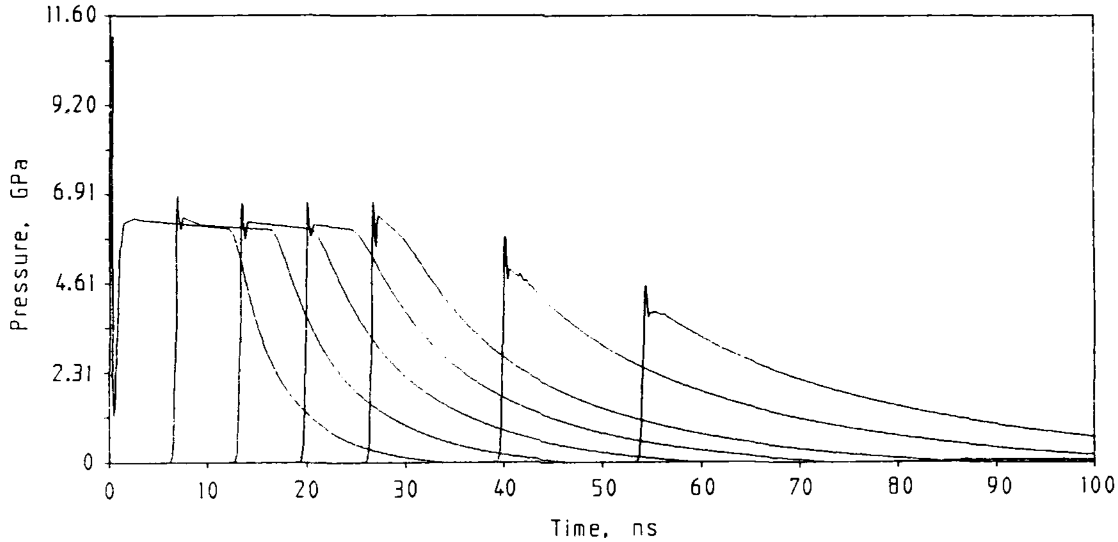

Figure 2: *Pressure profiles within the HNS target following impact at 2.5 mm/µs by a 25 µm thick Kapton disc. The first four profiles after impact are shown at successive depths of 25 µm. Thereafter, the profiles are shown at successive depths of 50 µm.*

As the code is non-reactive, it does not distinguish between impacts that lead to detonation and those that do not. The range of velocities chosen provides an opportunity to consider the change in attenuation as the velocity is increased beyond the threshold velocity. The results may be interpreted in terms of an initiation criterion of Walker-Wasley [4] form. The maximum depths at which initiation is predicted to occur may then be compared. Figures 3 and 4 show the results obtained for a 25 µm thick flyer plate at velocities of 1.5 and 3.5 mm/µs respectively. The pressures are shown at the same penetration distances as Figure 2 except for the last three in Figure 4 where the separation is 100 µm.

Figure 5 summarizes these results in a plot of the peak pressure as a function of distance into the target for various impact velocities and two flyer plate thicknesses (25 µm and 75 µm).

In Figure 6, $P^{2.4}t$ (the initiation criterion) is shown as a function of the penetration distance for various flyer plate velocities and thicknesses. The pressure and shock duration values are from the HULL output. The thick horizontal line represents the calculated value of this initiation criterion when the plate velocity is 2.7 mm/µs. Points below this line indicate a failure to initiate the explosive under this criterion.

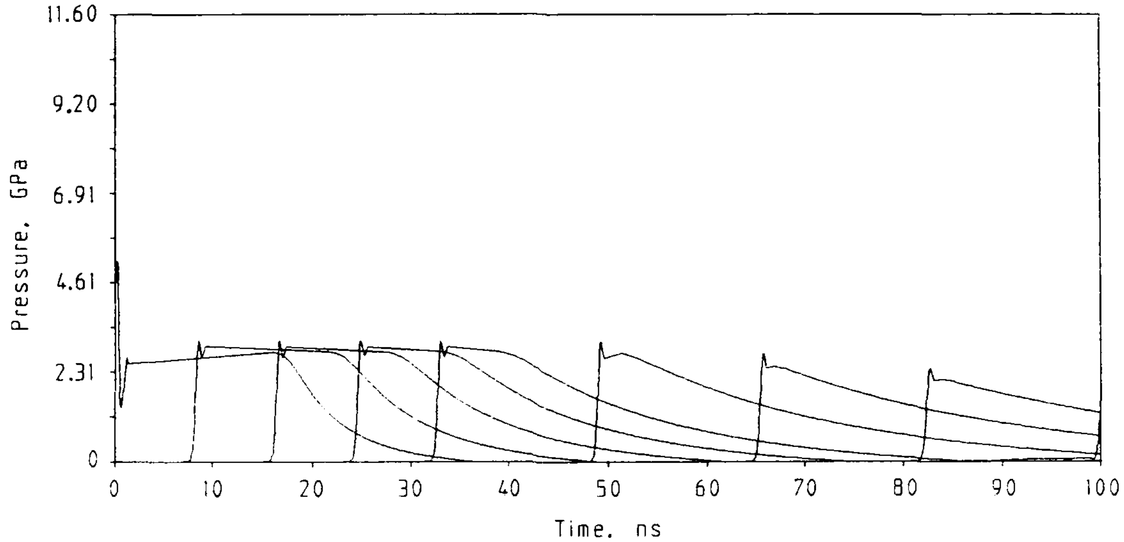

Figure 3: *Pressure profiles within the HNS target following impact at 1.5 mm/μs by a 25 μm thick Kapton disc. The first four profiles after impact are shown at successive depths of 25 μm. Thereafter, the profiles are shown as successive depths of 50 μm.*

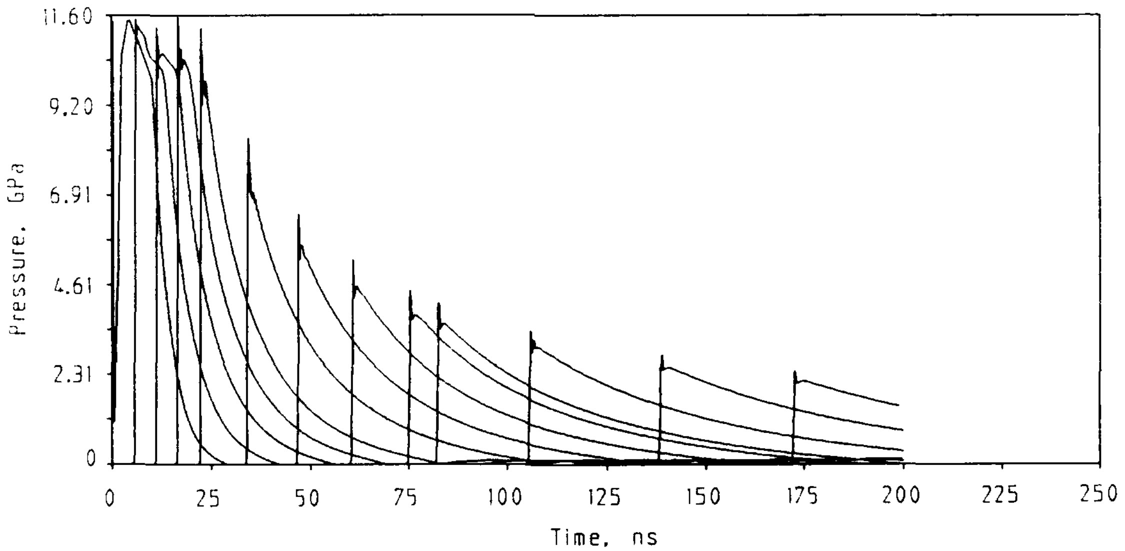

Figure 4: *Pressure profiles within the HNS target following impact at 3.5 mm/μs by a 25 μm thick Kapton disc. The first four profiles after impact are shown at successive depths of 25 μm. Thereafter, the profiles are shown at successive depths of 50 μm except for the last three which are shown at intervals of 100 μm.*

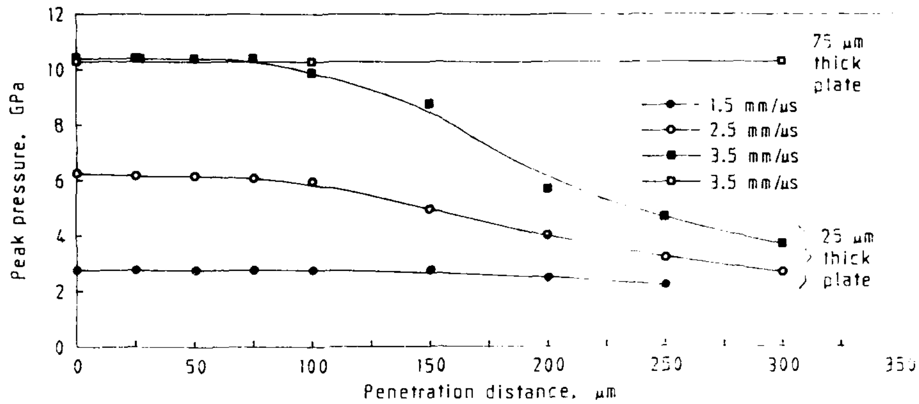

Figure 5: Graph showing the shock attenuation as a function of penetration distance for various impact velocities and flyer plate thicknesses of 25 µm and 75 µm.

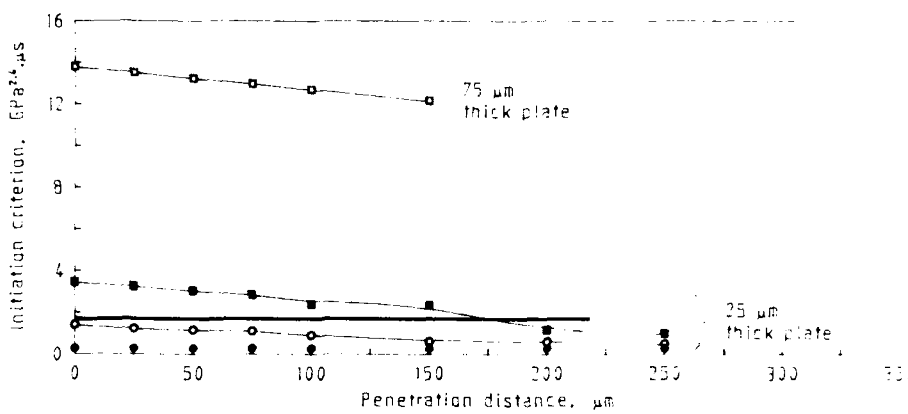

Figure 6: Graph showing the initiation criterion as a function of penetration distance for various flyer plate velocities and thicknesses.

4. Theory

At impact, the particle velocity u_p is common to both the flyer plate and the target. The shock reflected back into the flyer plate (U_{sf}) has a velocity given by equation 3 when the particle velocity is v_f-u_p. The shock velocity into the HNS (U_s) is given by equation 2. The reflected shock travels to the rear boundary of the flyer plate whereupon a reflected rarefaction wave returns to the interface between the flyer plate and the target. The transit time for this excursion is approximately,

$$\tau = \frac{2L}{U_{sf}} \tag{4}$$

where L is the thickness of the flyer plate. A rarefaction wave is then sent into the target.

To simplify this analysis, it was assumed that the component of the attenuation that is due to the rarefaction could be modelled independently. This would allow the results from such an analysis to be compared with the HULL output.

The simplified analysis assumes that U_r (rarefaction velocity in the target) can be related to U_s (shock velocity in the target) by:

$$U_r = \alpha \; U_s \tag{5}$$

where $\alpha > 1$ and constant. This relationship relies on the fact that the propagation velocity for disturbances behind the shock is greater than the shock velocity [1]. In reality α is not a constant and would decrease as the original shock wave loses energy to the medium and slows down [9].

Under these assumptions, the rarefaction wave overtakes the original shock wave at a distance:

$$d = \frac{2L \; \alpha \; U_s}{U_{sf}(\alpha - 1)} \tag{6}$$

into the target and after a time t following impact,

$$t = \frac{2L\alpha}{U_{sf}(\alpha - 1)} \tag{7}$$

The time to overtake is plotted as a function of α, (U_r/U_s) in Figure 7. The penetration curve displays the same features. It should be noted that if $\alpha = 1$ the rarefaction wave never catches up to the shock wave and that both the time and penetration distance are infinite.

A two dimensional analysis would need to include the effect of the unloading shock from the sides of the impacting plate. This unloading forms a Mach cone and further reduces the region of high pressure within the explosive. The cone angle, θ, is given by [9]:

$$\tan\theta = \frac{\sqrt{c^2 - (U_s - u_p)^2}}{U_s^2} \qquad (8)$$

$$\text{where } c = \frac{\sqrt{\partial P}}{\partial \rho} \qquad (9)$$

and ρ is the density.

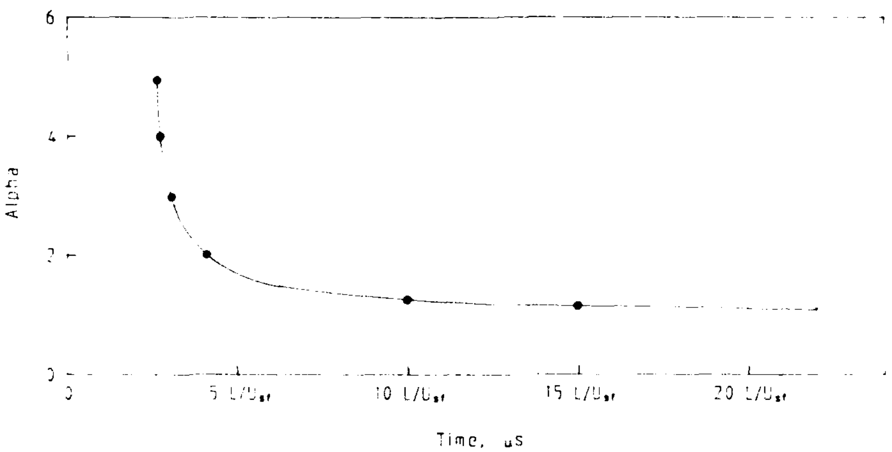

Figure 7: Smooth line joining the theoretical points which show the relationship between α, (U_s/C) and the time to attenuate a shock wave in a medium following flyer plate impact

5. Discussion

The pressure-time plots for the range of plate impacts shown in Figures 2, 3 and 4 indicate that the rate of attenuation depended on the impact velocity when employing a 25 µm thick disc. The shortest time for attenuation was found to occur at the highest velocity. For example, Figure 3 shows that a flyer plate impact at 1.5 mm/µs results in a minimal reduction in the peak pressure after 90 ns. Alternatively, for a flyer plate velocity of 3.5 mm/µs a significant reduction in peak pressure has already occurred by 80 ns (Figure 4). In both cases, however, the structure of the wave has changed.

Equations 2 and 3 can be used to calculate the particle velocity and shock velocities for a 25 µm thick flyer plate with a velocity of 3.5 mm/µs impacting a stationary HNS target. Equation 7 then predicts that the rarefaction overtakes

the shock in approximately 160 ns after impact for an α of 1.1. Given the simplifications involved, this calculation provides an indication of the upper bound to the attenuation time. The corresponding maximum penetration distance of 790 µm from equation 6 is beyond the range of Figure 5. An α of 1.2 predicts that the rarefaction overtakes the shock in approximately 85 ns. Thus for an impact velocity of 3.5 mm/µs a good approximation may be $1.1 < \alpha < 1.2$.

Figure 7 shows the strong relationship between α and the time to attenuate. Unfortunately the model cannot be used to compare attenuation times and penetration distances for different impact velocities as the relative α values are unknown. In fact, α will increase as the impact velocity increases.

Including the lateral release waves reduces the maximum penetration distance as calculated by HULL. For a flyer plate with a velocity between 1.5 and 3.5 mm/µs, the calculated Mach cone angle is between 41° and 50° from equation 8. The penetration distance for a 250 µm diameter flyer plate [10] is then found to be about 100 µm for an impact at 3.5 mm/µs and 140 µm for an impact at 1.5 mm/µs. Alternatively, for a 1.57 mm diameter flyer plate [3], the distances are 660 µm and 890 µm respectively. Equation 8 also provides an estimate for α. As the shock travels into the target at U_s, the side rarefactions travel at αU_s. The vector diagram of the addition of these two velocities gives:

$$\tan \theta = \alpha \tag{10}$$

For $41° < \theta < 50°$, then $0.9 < \alpha < 1.2$. This suggests an upper limit of 1.2 for α in good agreement with the earlier estimate. An $\alpha < 1$ results from the simplification of the shock interactions.

The rapid degradation of the pressure pulse by the encroaching rarefaction waves indicates that if initiation is to occur as defined by an initiation criterion of the $P^n t$ form, it must occur near the impact surface. This is shown in Figure 6 where for a 3.5 mm/µs flyer plate, initiation would be possible to a depth of approximately 200 µm; a distance equivalent to eight flyer plate thicknesses. Note that the Mach cone for 250 µm width flyer plates allow for a maximum penetration distance of about 100 µm. Under these conditions, it therefore seems that the initiation process is limited to a maximum depth of 100 µm.

As the impact velocity approaches the threshold velocity, Figure 6 suggests that initiation must occur close to the surface. Ultimately, a minimum volume of explosive must be shocked for initiation to begin. Below this minimum the shock wave continues to be attenuated. The minimum volume is probably due to a complex interaction of the particle size and/or the SSA and the strength of the shock wave. The minimum diameter of a detonation front that can be sustained by the explosive, the failure diameter, also provides a limit for the minimum volume. For the present work the width of the impacting plate is much greater than the failure diameter of the HNS. Above this minimum the energy released from the hot spots formed may be coupled to the shock wave. The shock wave may then build to detonation. Near the apex of the Mach cone the failure diameter may again limit the buildup process.

Measurement of the excess transit time for a detonation provides experimental evidence of the promptness of initiation. Excess time is the difference between the time measured for a detonation wave to be detected on the free surface of an explosive target following flyer plate impact at the other end, and the time taken for a reactive shock wave to travel that same distance. Using 50 µm thick flyer plates against pentaerythritol tetranitrate (PETN), Weingart et al [11] have shown that the excess transit time is close to zero when detonation does occur. A similar phenomenon occurs for HNS [3] with SSA < 10 m^2/g. Remembering that the excess transit time includes the time to ignite as well as the time to build up to detonation, the measured excess times indicate that initiation must occur very close to the explosive surface.

When a thicker flyer plate is employed, the initial shock duration is increased. A comparison between the HULL output for the 25 µm and 75 µm thick flyer plates with a velocity of 3.5 mm/µs (Figure 5) indicates that the peak pressure remains high for a much longer penetration distance for the thicker flyer plate.

The thicker flyer plate does not effect the Mach cone and therefore the maximum penetration depth for a shock of sufficient strength to cause initiation is still approximately 100 µm for a 75 µm thick, 250 µm wide flyer plate. To achieve greater penetration a wider flyer plate would be required.

According to Figure 6 lower threshold impact velocities for HNS are permitted as the thickness of the flyer plate increases from 25 µm to 75 µm. This is due to the longer shock duration time.

With further increases to the shock duration, the impact conditions change from short shock to sustained shock and the Waller-Wasley form of the initiation criterion no longer holds. The initiation mechanism also changes from one where the shock wave builds to detonation within the explosive medium, to one where the detonation begins at the shock interface. Thus increasing the thickness of the flyer plate to reduce the threshold impact velocity is of limited value when considering short shock initiation and the attendant penetration depth of the shock wave

6. *Conclusion*

HULL modelling has shown that significant shock attenuation occurs beyond 100 µm of the impact surface following thin (25 µm) flyer plate impact when the impact is close to the threshold velocity of HNS. This confirms that slapper detonator initiation must be prompt [11] and must occur within 4 flyer plate thickness of the impact surface.

The HULL code one-dimensional calculations and the theoretical analyses provided insight into experimentally determined initiation criteria. The possibility of further investigation including three dimensional analysis should be considered. These simulations may be employed to study the effect of plate planarity and tilt on the transmitted shock wave. Ultimately a reactive component will need to be included in the code. This will enable the target material to respond to the shock stimulus.

7. Acknowledgements

The authors wish to thank D.L. Smith for his help in the running of HULL and to D.D. Richardson for his valuable comments.

8. References

1. Duvall, G.E. (1961).
In response of metals to high velocity deformations, Eds. P.G. Shewmon and V.F. Zackay, NY USA, Interscience, p. 170.

2. Murr, L.E. (1988).
In shock waves for industrial applications, Ed. L.E. Murr, NJ USA Noyes p. 86.

3. Schwarz, A.C. (1981).
Study of factors which influence the shock initiation sensitivity of hexanitrostilbene (HNS) SAND80-2372.

4. Walker, F.E. and Wasley, R.J. (1969).
Critical energy for shock initiation of heterogeneous explosives, *Explosivstoffe*, 17, 9.

5. Matuska, D.A. and Osborn, J.J. (1987).
HULL Documentation, Orlando Technology Inc. FL. USA.

6. Davies, F.W., Shrader, J.E., Simmerschied, A.B. and Riley, J.F. (1976).
The equation of state and shock initiation of HNS II, *6th Symposium (International) on Detonation*, Office of Naval Research Arlington VA. p. 740.

7. Stanton, P. (1988).
Private Communication SNL, USA.

8. Kipp, M.E. and Setchell, R.E. (1989).
A shock initiation model for fine-grained hexanitrostilbene. Preprints *9th Symposium (International) on Detonation*, Office of Naval Research Arlington VA. p. 103.

9. Zel'dovich, Ya.B. and Raizer, Yu.P.
Physics of shock waves and High Temperature Hydrodynamic Phenomena. Vol II, Academic Press NY 1967 p. 746 - 750.

10. Waschl, J., Richardson, D.D. and Northeast, E. (1991). *Slapper detonator studies with explosive HNS (U)* (MRL Technical Report MRL-TR-91-1) (Confidential). Maribyrnong, Vic.: Materials Research Laboratory.

11. Weingart, R.C., Lee, R.S., Jackson, R.K. and Parker, N.L. (1976). Acceleration of thin flyers by exploding metal foils : Applications to Initiation Studies, *6th Symposium (International) on Detonation*, Office of Naval Research Arlington VA. p. 653.

SECURITY CLASSIFICATION OF THIS PAGE **UNCLASSIFIED**

DOCUMENT CONTROL DATA SHEET

REPORT NO.	AR NO.	REPORT SECURITY CLASSIFICATION
MRL-TN-597	AR-006-840	Unclassified

TITLE

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REPORT DATE	TASK NO.	SPONSOR
February, 1992	DST 89/149	DSTO

FILE NO.	REFERENCES	PAGES
G6 4 8-3963	11	18

CLASSIFICATION LIMITATION REVIEW DATE	CLASSIFICATION RELEASE AUTHORITY
	Chief, Explosives Ordnance Division

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KEYWORDS

Shock Wave Attenuation Shocks in Explosives	Modelling Shocks	Short Pulse Duration

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